1. Final Report On

Real-Time Control for Optimal Liquid Rocket Combustor Performance

Research Performed at

School of Aerospace Engineering
Georgia Institute of Technology

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2. Program Objectives

The primary objective of this program is to investigate/develop a control approach that will enable *Intelligent Liquid Rockets* to operate with an optimal stability margin and efficiency of propellants utilization. This goal is pursued by developing "smart" injectors that can be manipulated during flight to change the characteristics of their sprays in order to provide ***maximum specific impulse without loss of stability.*** Additionally, this program is investigating the performance and integration of the sensors, actuators and control/logic of the active control system of the engine as well as the fundamental processes that control the performance of liquid rocket combustors that employ the developed "smart" injectors.

3. Status of Effort

To meet the goals of this program, a "smart" liquid fuel injector whose spray pattern can be modified by controlling the flow rates of two coaxial, counter swirling, oxidizer (air) streams that control the characteristics of the fuel spray was developed and tested under cold-flow conditions and in combustion experiments. The cold flow experiments have clearly shown that it's possible to drastically change the characteristics of the fuel spray by changing the relative flow rates of the two oxidizer streams. The performance of this "smart" injector was studied in two combustors that were developed for this study. The first has one "smart" injector at the center of its injector plate and the second seven such injectors uniformly distributed on the injector plate. Both combustors have quartz walls to allow extensive access for optical diagnostics. Open loop tests with the single injector combustor showed that the "smart" injector can suppress ***longitudinal combustion instabilities*** by varying the split between the flow rates of the two controlling oxidizer streams (see AIAA papers 2003-4937, 2004-1034 and ASME Paper # GT2005-69138). Furthermore, open loop tests with the seven ("smart") injectors combustor, which emulated the configuration of a liquid rocket engine, have shown that the utilized injector arrangement can suppress both ***longitudinal and tangential*** (f~4600Hz) combustion instabilities in liquid rockets (see AIAA-2004-4029 and ASME # GT2005-68869).

4. Accomplishments/New Findings

The original goal of the study was to develop an approach for suppressing combustion instabilities in liquid rocket engines (LRE) combustors by "slow" variation of design parameters, which can cause instabilities in liquid rocket combustors. In pursuit of this goal, the AFOSR program has been investigating a control approach that would enable ILRC to operate with an optimal stability margin and efficiency of propellants utilization. To attain this goal, the current program has been investigating a novel, "slow" active control approach for preventing/minimizing the onset of detrimental combustion instabilities in liquid rockets. Specifically, in contrast to earlier active control approaches that damped instabilities by modulating the fuel injection rate at the frequency of the instability and appropriate gain and phase, the investigated approach sought to "actively" damp the instability by a "one-time" action that modified the properties of the combustion process. This approach was motivated by the knowledge that one of the

conditions for the occurrence of combustion instabilities is that the characteristic combustion time (e.g., time required to evaporate/burn a typical droplet) approximately equal the characteristic acoustic time (i.e., period of the unstable mode). It, thus, follows that if one could change the characteristic combustion time in an unstable engine, the instability would be damped because the combustion time would no longer equal the acoustic time. To accomplish this, it would be necessary to develop capabilities for modifying the characteristics of the combustion process and, thus, the characteristic combustion time. The development of such capabilities and demonstrating that they could be used to damp combustion instabilities has been the goal of the AFOSR program.

To demonstrate the feasibility and practicality of the above discussed "one-time" control approach, the current program investigated the use of "smart" injectors with capabilities for changing the characteristics of their spray and, thus, the combustion time. Additionally, this program has been investigating the performance and integration of the sensors, actuators and control/logic of the active control system of the engine as well as the fundamental processes that control the performance of liquid rocket combustors that employ the developed "smart" injectors.

To meet the goals of this program, a "smart" liquid fuel injector whose spray characteristics can be controlled was developed and investigated. This injector, installed in the developed combustor, is shown in Figure 1. The developed injector is supplied with an axial fuel stream at its bottom and primary and secondary, counter swirling, air streams with controllable flow rates at two axial positions downstream of the fuel injection point. To produce a fuel spray, the primary air stream is injected directly into the fuel stream near the location of the fuel nozzle and the secondary air stream impinged upon the generated spray when it exits the primary injector housing, thus further affecting the spray properties. Combustion occurs after the two streams mix in a recirculation zone downstream of the injector face.

Cold flow investigations of the "smart" injector have shown that it's possible to significantly change the characteristics of its spray by changing the relative flow rates of the two oxidizer streams, see Figure 2, where the ratio of the two air streams is denoted by the parameter K. It should be noted that while the value of K is changed, the total flow rate of air into the injector is fixed. Figure shows images of the sprays generated for various values of K in a laser light sheet. It shows that as the ratio of the primary to secondary air flow rates decreases (while the total air flow rate is fixed), the value of K decreases and the spray's shape changes from a nearly radial spray to a jet like spray.

The control that could be attained with the "smart" injector was studied in two combustors that were developed for this study. The first, shown in Figure , has one "smart" injector at the center of its injector plate and the second has seven "smart" injectors uniformly distributed on the injector plate, see Figure . Both combustors have quartz walls to allow extensive access for optical diagnostics and their performance at various equivalence ratios and injector "operating conditions" (i.e., K values) were studied using the diagnostic capabilities shown in Figure 1 and Figure .

Studies with the ***single-injector combustor*** showed that the mass flow rate ratios of the primary and secondary swirling air streams (i.e., the value of *K*) strongly affects the fuel spray properties, flow field, and, thus, combustion instabilities. For relatively low values of *K*, the injector produced a toroidal recirculation zone in the vicinity of the combustor

wall near the combustor inlet. The size of this zone increased in the downstream direction as the magnitude of K increased. It was also determined that for low K values the characteristics of ***longitudinal*** instabilities strongly depend upon the equivalence ratio. On the other hand, when K is relatively large, a recirculation zone develops along the combustor centerline and the RMS pressure amplitude of the instability is nearly constant at about 6% of the combustor's mean pressure over the entire range of investigated equivalence ratios. These findings clearly demonstrate that the magnitude of K can affect the characteristics of the combustion process and associated instabilities, as had been expected. Additionally, open loop control tests with the single-injector combustor, see Figure , showed that the "smart" injector can suppress ***longitudinal combustion instabilities*** by varying the magnitude of the parameter K, see Refs.1 and. 3

The investigation of the seven-injector combustor, which better emulated the design of a liquid rocket engine, showed that both longitudinal and tangential (f~4600Hz) instabilities are excited in this combustor at different operating conditions. Follow up, open loop, tests of this seven-injector combustor have shown that by controlling the parameter K and, thus, the characteristics of the sprays it is possible to suppress both ***longitudinal and tangential*** combustion instabilities[5]. To demonstrate the application of the developed approach in the damping of combustion instabilities, an experiment was performed in which transverse combustion instability was damped by changing the magnitude of K. In this experiment, described in Figure , the combustor was initially operating stably until the equivalence ratio was increased, see Figure -a. This excited tangential mode of the combustor, see Figure -c. After a few seconds of unstable operation, the value of K was changed from 83/17 to 50/50 (see Figure -a,b), resulting in the suppression of the instability (see Figure -c). It's noteworthy that a longitudinal mode was excited for a very short period of time when the equivalence ratio and K were changed.

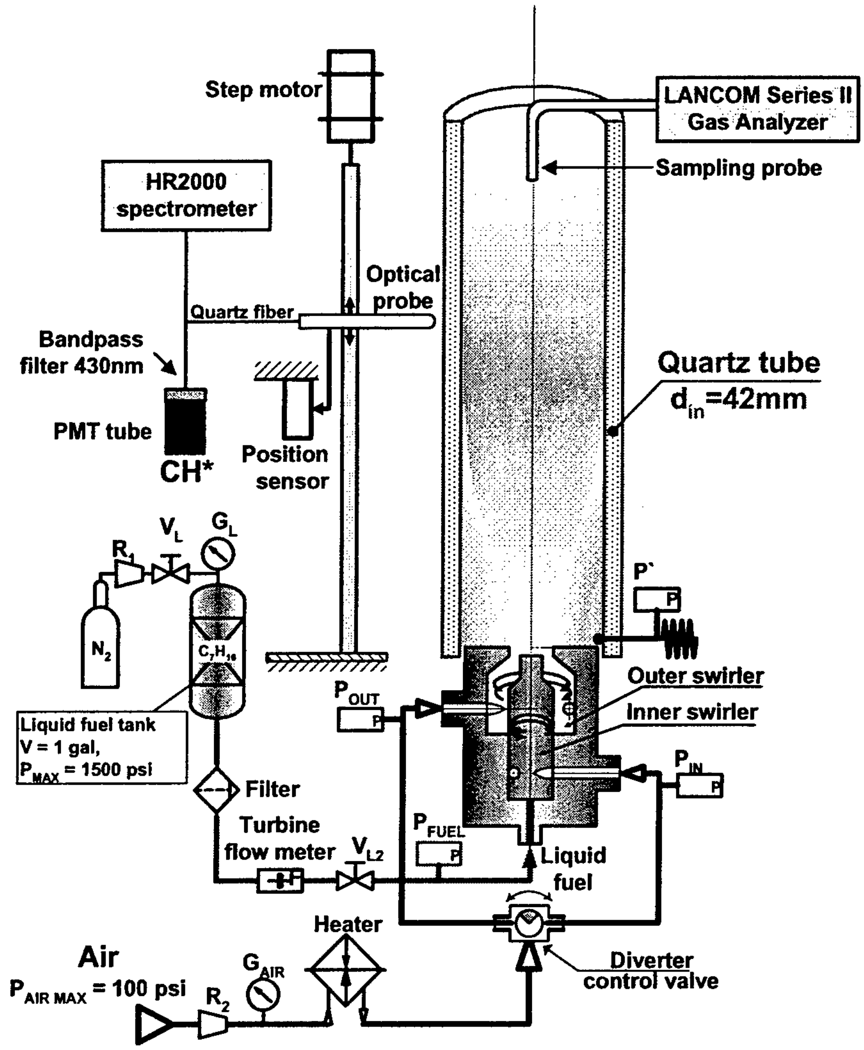
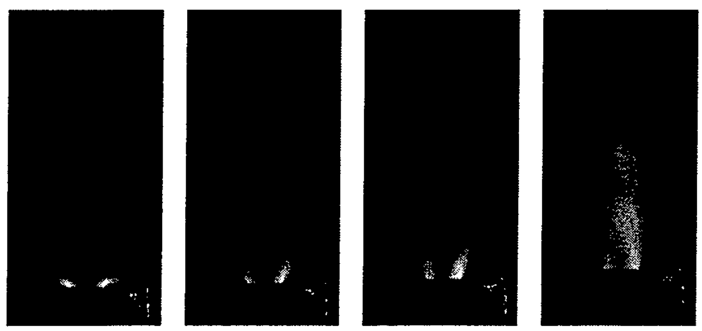


Figure 1. A schematic of the experimental setup used to study a the performance of a single "smart" injector.



(a) (b) (c) (d)

Figure 2. Laser sheet images of fuel spray at different inner/outer swirling air flow rates ratios, K, for $m_{fuel} = 0.5$ g/s and $m_{air} = 9.2$ g/s. (a) $K = 25/75$; (b) $K = 37.5/62.5$; (c) $K = 50/50$; (d) $K = 75/25$.

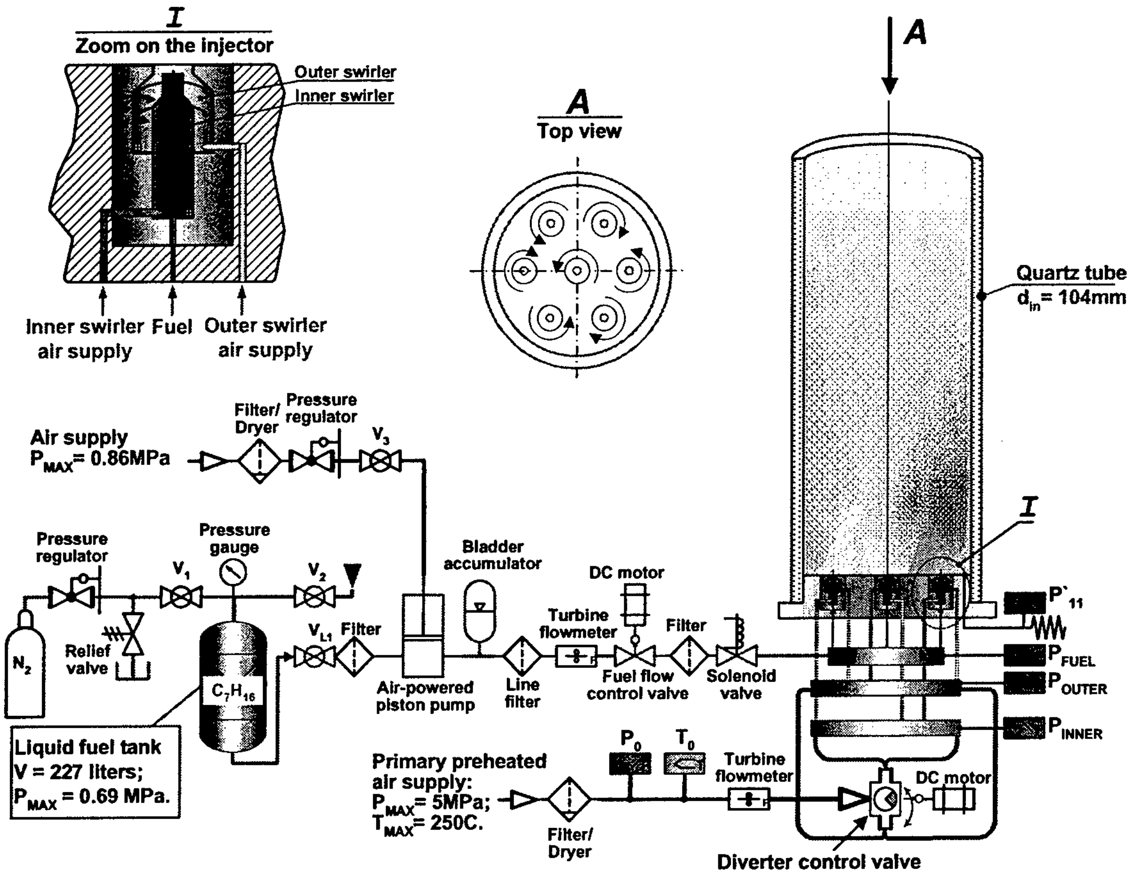


Figure 3. A schematic of the seven-"smart" injectors experimental setup.

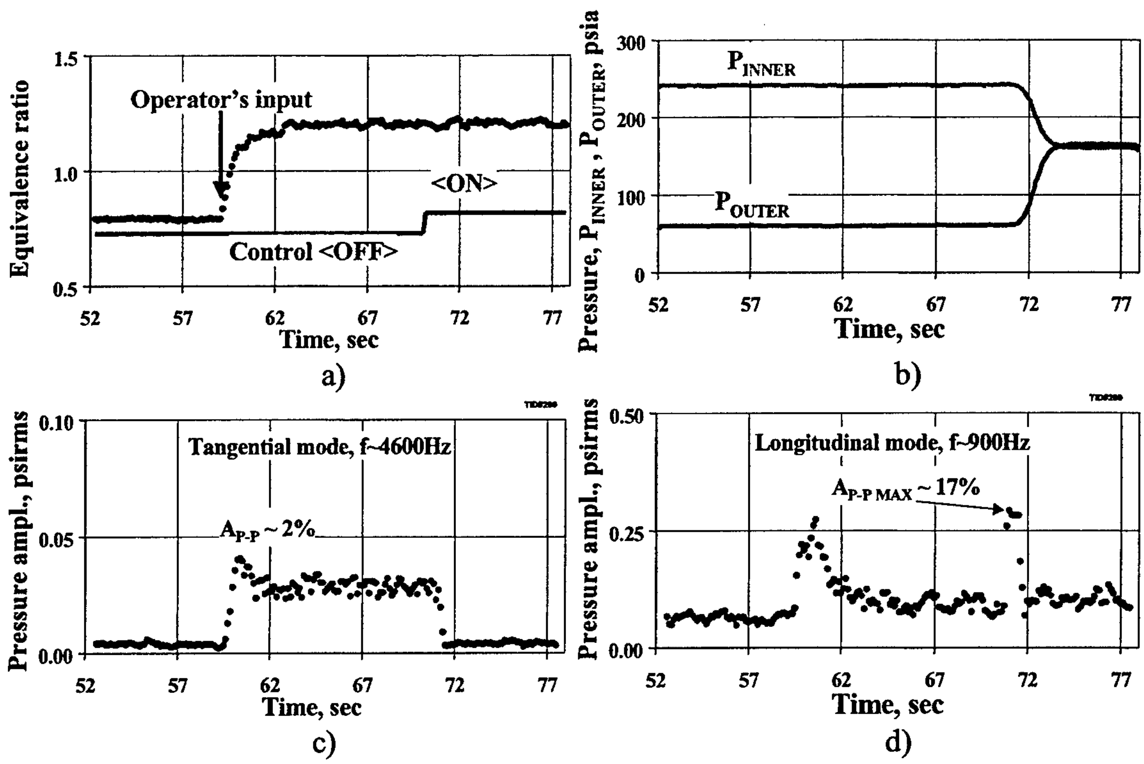


Figure 4. Demonstration of control of instabilities by variation of *K*.

In summary, the ongoing AFOSR efforts have developed a new approach for damping combustion instabilities. This approach employs "smart" rocket injectors to modify the characteristics of the combustion process. The results of this study strongly suggest that "smart" injectors could be also used to control/increase the stability margin of the engine.

Additional results of our studies are provided in AIAA papers # 2003-4937, # 2004-1034 and # 2004-4029, as well as in ASME Papers # GT2005-69138, # GT2005-68869, and # GT2005-68448 which are provided in the Appendix I of this report.

5. Personnel supported

Dr. Ben T. Zinn - David S. Lewis Jr. Chair and Regents Professor
Dr. Yedidia Neumeier – Principal Engineer and Adjunct Faculty
Dr. Eugene Lubarsky – Senior Research Engineer
Mr. Dmitriy Scherbick – Visiting Research Engineer
Dr. Alexander Bibik – Research Scientist II
Dr. Jaeyon Lee – formerly Ph.D. Student and Graduate Research Assistant
Mr. Ted J. Conrad – Ph.D. Student and Graduate Research Assistant

6. Publications

1. T.J. Conrad, A. Bibik, J.-Y. Lee, D. Shcherbik, E. Lubarsky, and B. T. Zinn, "Control of Combustion Instabilities by Fuel Spray Modification Using Smart Fuel Injector", AIAA paper #2003-4937, 39TH AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 20-23 July 2003, Huntsville, Alabama.
2. Jae-Yeon Lee, "Fast and Slow Active Control of Combustion Instabilies in Liquid Fueled Combustors" A PhD Dissertation Presented to the Academic Faculty, Georgia Institute of Technology, August, 2003.
3. Conrad, T. J., Bibik, A., Scherbik, D., Lubarsky, E., and Zinn, B. T., "Slow" Control of Combustion Instabilities by Fuel Spray Modification Using Smart Fuel Injector", AIAA Paper No. 2004-1034, 42nd Aerospace Science Meeting & Exhibit, January 5-9, 2004/Reno, NV.
4. Conrad, T. J., Bibik, A., Scherbik, D., Lubarsky, E., and Zinn, B. T., Control of Instabilities in Liquid Fuel Combustor by Modification of the Reaction Zone Using Smart Fuel Injector", AIAA Paper No. 2004-4029, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 11-14 July 2004, Fort Lauderdale, Florida.
5. Zinn, B., T., " Smart Combustors – Just Around the Corner", ASME Paper # GT2005-69138, The 50th ASME Gas Turbine and Aeroengine Technical Congress and Exposition, 6-9 June 2005 Reno-Tahoe, Nevada.
6. Bibik, A., Conrad, T. J., Scherbik, D., Lubarsky, E., and Zinn, B. T., "Modification of the Reaction Zone Using a Smart Fuel Injector for Control of Instabilities in Liquid Fueled Combustors", ASME Paper # GT2005-68869, The 50th ASME Gas Turbine and Aeroengine Technical Congress and Exposition, 6-9 June 2005 Reno-Tahoe, Nevada.
7. Bibik, A., Conrad, T. J., Scherbik, D., Lubarsky, E., and Zinn, B. T., "Onset of Combustion Instabilities During Transition to Supercritical Fuel Injection in High Pressure Combustor", ASME Paper # GT2005-68448, The 50th ASME Gas Turbine and Aeroengine Technical Congress and Exposition, 6-9 June 2005 Reno-Tahoe, Nevada

7. Interactions/Transitions

Presentations:

"Suppression of Instabilities in Liquid Fueled Combustor by Variation of Fuel Spray Properties," ASME Turbo Expo 2003, Atlanta, GA, June 16-19, 2003.

"Suppression of Instabilities in Gaseous Fuel High-Pressure Combustor Using Non-Coherent Oscillatory Fuel Injection," ASME Turbo Expo 2003, Atlanta, GA, Jun. 16-19, 2003.

"Active Control of Combustion Oscillations by Non-Coherent Fuel Flow Modulation AIAA/CEAS Aeroacoustics Conference and Exhibit, Hilton Head, SC, May 12-14, 2003.

"Control of Combustion Instabilities by Fuel Spray Modification Using Smart Fuel Injector," AIAA 39TH AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 20-23 July 2003, Huntsville, Alabama.

"Control of Severe Combustion Instabilities by Non-Coherent Fuel Flow Modulation," 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, AIAA-2004-0634. Jan. 5-8, 2004.

"Slow Control of Combustion Instabilities," 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, AIAA-2004-1034. Jan. 5-8, 2004

"Control of Instabilities in Liquid Fuel Combustor by Modification of the Reaction Zone Using Smart Fuel Injector," 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 11-14 July 2004, Fort Lauderdale, Florida.

"Smart Combustors – Just Around the Corner" Scholar Lecture given by Dr. B.T. Zinn on June 6th 2005 at the 50th ASME Gas Turbine and Aeroengine Technical Congress and Exposition, Reno-Tahoe, Nevada.

"Modification of the Reaction Zone Using a Smart Fuel Injector for Control of Instabilities in Liquid Fueled Combustors", at the 50th ASME Gas Turbine and Aeroengine Technical Congress and Exposition, 6-9 June 2005 Reno-Tahoe, Nevada.

"Onset of Combustion Instabilities During Transition to Supercritical Fuel Injection in High Pressure Combustor", at the 50th ASME Gas Turbine and Aeroengine Technical Congress and Exposition, 6-9 June 2005 Reno-Tahoe, Nevada.

a. **Consultative and advisory functions to other laboratories and agencies.**
b. **Transitions**

8. New discoveries

The above discussed approach for "slow" active control of combustion instabilities using the developed "smart" liquid fuel injectors.

9. Honors/Awards:

Dr. Zinn received the AIAA Air Breathing Propulsion Award on July 22, 2003 "For outstanding contributions to the understanding and active control of unsteady combustion phenomena in air breathing propulsion systems."

Dr. Zinn was selected to give the Fowler lecturer at Texas A & M University on "Smart Combustors – Just Around the Corner," February, 2004.

Dr. Zinn was invited to give a plenary lecture on "Control of Combustion Processes at the International Workshop on Lean Combustion Technology II, Tomar, Portugal, April 24-29, 2004.

Dr. Zinn was selected to give the IGTI (International Gas Turbine Institute) Scholar plenary lecture on June 6th 2005 at the 50th ASME Gas Turbine and Aeroengine Technical Congress and Exposition, Reno-Tahoe, Nevada.

Dr. Zinn received the IGTI (International Gas Turbine Institute) 2005 Aircraft Engine Technology Award "For sustained personal creative contributions to aircraft engine technology in the areas of aircraft engine design and/or research and development performed in an industrial, academic or research laboratory environment".

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14. ABSTRACT

To meet the goals of this program, a "smart" liquid fuel injector whose spray pattern can be modified by controlling the flow rates of two coaxial, counter swirling, oxidizer (air) streams that control the characteristics of the fuel spray was developed and tested under cold-flow conditions and in combustion experiments. The cold flow experiments have clearly shown that it's possible to drastically change the characteristics of the fuel spray by changing the relative flow rates of the two oxidizer streams. The performance of this "smart" injector was studied in two combustors that were developed for this study. The first has one "smart" injector at the center of its injector plate and the second seven such injectors uniformly distributed on the injector plate. Both combustors have quartz walls to allow extensive access for optical diagnostics. Open loop tests with the single injector combustor showed that the "smart" injector can suppress longitudinal combustion instabilities by varying the split between the flow rates of the two controlling oxidizer streams (see AIAA papers 2003-4937, 2004-1034 and ASME Paper # GT2005-69138).

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